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14. ABSTRACT

The research effort supported under this grant ended 31 July 2004. A highlight of progress during the final fiscal year was a clear theoretical explanation of and solution to. the model mismatch stability problem generally associated with state-of-the-art adaptive control design methods. The source of these model-mismatch instability problems was traced to the implicit use of absolute-error cost functions and/or use of assumption-driven cost functions. These cost-functions were shown via counter-example to he capable of giving preference to destabilizing control—laws in some cases involving model—mismatch. Having identified the model-mismatch problem, a fix was also identified, which is to employ a data-driven input-output-gain related cost function for adaptive control-law selection. This progress was enabled by theory that explains the synthesis of adaptive control processes in terms of control law unfalsification

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ROBUST CONTROL, FEEDBACK AND LEARNING: DATA-DRIVEN METHODS

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Objectives

This three-year research program focuses on developing and improving engineering techniques for robust and adaptive control system design, with particular emphasis on the need for *data-driven* design methods that are suited to situations in which available mathematical models are poor or unreliable. The work revolves around recently developed analytic tools for nonlinear and adaptive control.

Status of Effort

The research effort supported under this grant ended 31 July 2004. A highlight of progress during the final fiscal year was a clear theoretical explanation of, and solution to, the model-mismatch stability problem generally associated with state-of-the-art adaptive control design methods. The source of these model-mismatch instability problems was traced to the implicit use of absolute-error cost functions and/or use of assumption-driven cost functions. These cost-functions were shown via counter-example to be capable of giving preference to destabilizing control-laws in some cases involving model-mismatch. Having identified the model-mismatch problem, a fix was also identified, which is to employ a data-driven input-output-gain related cost function for adaptive control-law selection. This progress was enabled by theory that explains the synthesis of adaptive control processes in terms of control law unfalsification. Adaptive feedback systems designed using the unfalsified control approach together with a data-driven gain-related cost function consistently yield robust fast-adaptive control laws that can quickly identify and remove destabilizing candidate control laws irrespective of plant-model mismatch. Potential applications include the design of fast adaptive fail-safe recovery systems for battle-damaged aircraft control systems, missile guidance systems, and communication networks.

Accomplishments

The past year has resulted in a number publications covering not only our breakthroughs identifying and fixing the model-mismatch instability problems of conventional adaptive control design ([12],[14]) but also fundamental advances in nonlinear stability theory ([2],[3],[6],[15]), and several interesting theoretical and design studies applying of our research results to the analysis and design of decentralized adaptive transmitter-power adjustment strategies for cellular communication networks ([4][7][10][11][13][16]). Also produced were survey articles

examining aspects of controller unfalsification ([1],[8]), and more specialized studies concerning specific techniques for computing unfalsified cost levels for use in adaptive control with certain classes of non-model-mismatch tolerant cost-functions ([5], [9]). The nonlinear stability multiplier counterexample [15], and the breakthrough advances in mismatch-tolerant, fast-adaptive control design technology reported in [12] and [14] are further described below.

This is the third year in a row in which we have had major new successes in advancing the theory and methods for multiplier-based **nonlinear stability** analysis. Two years ago, we reported a new, more precise nonlinear stability criterion for systems with repeated single-input-single-output (SISO) monotone nonlinearities like rate and position limits ubiquitous in the mechanical actuators of missile and aircraft flight control systems, as well as in industrial control systems. The result provided a very useful convex characterization of the entire class of multiplier matrices $M(s)$ that preserve dissipativeness of repeated diagonal nonlinearities, like the saturation and rate-limit nonlinearities found ubiquitously in aerospace control systems. Last year, we took the repeated nonlinearity concept much further, with a new result that gives the entire class of positivity preserving stability multipliers for **repeated MIMO nonlinearities** [3]. Our repeated MIMO nonlinearity nonlinear stability result is useful for aerospace systems in which several elements having similar shape (e.g., two wings, or four fins, or several identical flexible truss elements, solar panels, or robotic arms). This past year, we have examined the fundamental **limits of multiplier stability criteria**, proving that while they ensure stability multiplier based nonlinear stability criteria cannot guarantee continuity of response in the face of time-varying input signals ([15]); this latest result was proved using our newly developed nonlinear instability theorem [2] to help construct a counter-example demonstrating transient response discontinuity in the presence of certain time-varying input signals. So, though multiplier-based nonlinear stability criteria do indeed ensure a stable control system response, the system's transient response behavior in the presence of set-point changes or other time-varying command inputs may nevertheless not be precisely predictable or even repeatable.

In the data-driven **adaptive control and learning** systems area, we have constructed counter-examples [14] showing that, unlike our unfalsified controllers with L_{2e}-gain related cost functions, state-of-the-art multi-model adaptive control systems are in general not able to reliably distinguish stable and unstable behavior when model-mismatch exceeds certain thresholds. To fix this problem, we have built on the *hysteresis switching lemma* of Morse et al (*IEEE Trans.*, 1992) to develop a theorem in [12] that clearly articulates optimal steps to be followed in designing adaptive control laws selectors that efficiently and reliably overcome this problem—see Figure 1. The *hysteresis switching lemma* implied that a switched sequence of controllers $K(t_i)$ (i = 1,2,...) that minimize the current unfalsified cost at each switch-time t_i will also stabilize if the cost for each fixed controller K has the properties that (1) it is a monotone increasing function of time and (2) it is uniformly bounded above if and only if K is stabilizing. But, Morse et al. were able to demonstrate these properties for adaptive methods only by introducing assumptions on the plant. Now using our theorem in [12], we can directly design adaptive control selectors that quickly, reliably and robustly sift candidate controllers based on all available evidence to minimize unfalsified cost levels and simultaneously ensure that stability goals are attained without such plant assumptions. With our method, destabilizing controllers are never retained when a stabilizing candidate controller is available, irrespective of model mismatch and irrespective of whether *standard assumptions* or other prior beliefs hold, so we get

robustly stabilizing adaptive control irrespective of plant model-mismatch [12]. In several design studies, we have demonstrated that our unfalsified control approach with a monotone L_{2e}-gain related cost function converges quickly and reliably in real time to a stabilizing controller that robustly achieves specified performance goals, often converging within a fraction of an unstable plant's fastest unstable time constant. This speed of adaptive response means that "bursting phenomena" that plague conventional slow adaptive systems do not occur, even in the absence of persistently exciting disturbance signals. Because our unfalsified adaptive systems perform reliably irrespective of plant model mismatch, they have the potential to reliably achieve rapid real-time failure recovery for battle-damaged aircraft and similar systems.
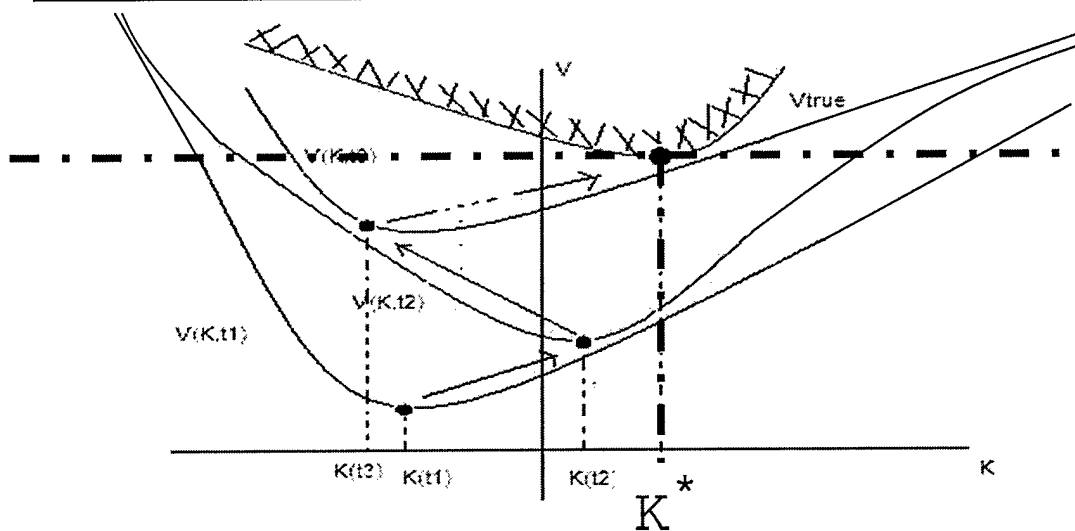
Figure 1: Our L_{2e}-gain related cost functions satisfy the Morse lemma without plant assumptions, so we get robustly stabilizing adaptive control irrespective of plant model-mismatch [12].

Personnel Supported

Michael G. Safonov, Professor & Principal Investigator
Rengrong Wang, Graduate Research Assistant
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Publications

[1]   P. Brugarolas and M. G. Safonov. Learning about dynamical systems via unfalsification of hypotheses. Int J. Robust and Nonlinear Control, 14(11):933–943, July 25, 2004. Special Issue on Robust control from data: Direct and model based approaches.

[2]   Vincent Fromion and Michael G. Safonov. Popov-Zames-Falb multipliers and continuity of the input/output map. Automatica, submitted 06/2004. Preprint in Proc. IFAC Symp. on Nonlinear Control Systems, NOLCOS 2004. September 2004.

[3] Ricardo Mancera and Michael G. Safonov. Stability multipliers for repeated MIMO nonlinearities. Systems and Control Letters, submitted May 2004.

[4] Ayanendu Paul, Mehmet Akar, Michael G. Safonov, and Urbashi Mitra. Adaptive distributed power control in cellular communication networks. IEEE Transactions on Neural Networks, submitted November, 2003, under review. Special Issue on Adaptive Learning Systems in Communication Networks.

[5] F. B. Cabral and M. G. Safonov. Unfalsified model reference adaptive control using the ellipsoid algorithm. Int. J. Adaptive Control and Signal Processing, to appear 2004. Special issue on Iterative Modeling and Control.

[6] V. Fromion, M. G. Safonov, and G. Scorletti. Necessary and sufficient conditions for Lur'e sys-tem incremental stability. In Proc. European Control Conf., Cambridge, England, September 1–4, 2003.

[7] A. Paul and M. G. Safonov. Model reference adaptive control using multiple controllers & switching. In Proc. IEEE Conf. on Decision and Control, Maui, HI, December 9-12, 2003. IEEE Press, New York.

[8] F. B. Cabral and M. G. Safonov. Unfalsified model reference adaptive control using the ellipsoid algorithm. In Proc. IEEE Conf. on Decision and Control, Maui, HI, December 9-12, 2003. IEEE Press, New York.

[9] F. B. Cabral and M. G. Safonov. Fitting controllers to data: the MIMO case. In Proc. American Control Conf., Boston, MA, June 30 – July 2, 2004.

[10] A. Paul, M. Akar, M. G. Safonov, and U. Mitra. Necessary and sufficient conditions for stability of a class of second order switched systems. In Proc. American Control Conf., Boston, MA, June 30 – July 2, 2004. I

[11] A. Paul, M. Akar, and M. G. Safonov. Power control for wireless networks using multiple controllers and switching. In Proc. American Control Conf., Boston, MA, June 30 – July 2, 2004.

[12] M. Stefanovic, W. Wang, and M. G. Safonov. Stability and convergence in adaptive systems. In Proc. American Control Conf., Boston, MA, June 30 – July 2, 2004.

[13] A. Paul, M. Akar, U. Mitra, and M. G. Safonov. A switched system model for stability analysis of distributed power control algorithms for cellular communications. In Proc. American Control Conf., Boston, MA, June 30 – July 2, 2004. IEEE Press, New York.

[14] R. Wang, M. Stefanovic, and M. G. Safonov. Unfalsified direct adaptive control using multiple controllers. In Proc. AIAA Guidance, Navigation and Control Conf., Providence, RI, August 16–19, 2004.

[15] Vincent Fromion and Michael G. Safonov. Popov-Zames-Falb multipliers and con-trinity of the input/output map. In Proc. IFAC Symposium on Nonlinear Control Systems (NOLCOS 2004), Stuttgart, Germany, September 1–3, 2004, to appear.

[16] Mehmet Akar, Urbashi Mitra, and Michael G. Safonov. Stable distributed power control for rate-varying multimedia CDMA systems. In Proc. IEEE Conf. on Decision and Control, Paradise Island, Bahamas, December 9-12, 2004, submitted.

Interactions/Transitions
Participation in Meetings/Conferences:
- IEEE Conf. On Decision and Control, December 2003
- American Control Conference, June 2004
- AFOSR Workshops on Dynamics and Control, August 2004
- AIAA Conf on Guidance Navigation and Control, Aug2004
- IFAC Symp. on Nonlinear Systems, September 2004

Consultive and Advisory Functions. N/A
Transitions.
Commercial Robust Control Software

Enabling Research:	Robust control theory, including LMI/BMI methods
Performer:	Michael G. Safonov, USC (213) 740-4455
Customer:	MathWorks, Inc., Natick, MA. Roy Lurie, (508) 647-7000
Result:	Revamped MATLAB advanced control system design software product *Robust Control Toolbox* — see G. J. Balas, M. G. Safonov, A. K. Packard, and R. Y. Chiang. Next generation of tools for robust control. Proc. American Control Conf., Boston, MA, June 30-July 2, 2004. ftp://routh.usc.edu/pub/safonov/safo04f.pdf

New Discoveries, Inventions, or Patent Disclosures.   N/A

Honors/Awards

M. G. Safonov	Invited lecturer, NATO LS SCI-166, *Achieving Successful Robust Integrated Control System Designs for 21st Century Military Applications – Part II*, 2005.
M. G. Safonov	Bellman Award Chair, American Automatic Control Council, 2004 & 2005
M. G. Safonov	Fellow IEEE, awarded 01 January 1989